# BARDEN INLET, N.C.
# A CASE STUDY OF INLET MIGRATION

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## ABSTRACT

The migratory pattern of a small coastal inlet was examined in terms of the factors generally acknowledged to control inlet behavior. That is, the tidal discharge which acts to flush the inlet and, on the other hand, the intrusive littoral materials depositing in the inlet environment. Specifically, a "flow conveyance index" was computed and compared to shoreline movements. The "flow conveyance index" was defined as the ratio of the mean distribution of the overall planform area of the throat of the inlet to the mean distribution of the planform areas of shoals within the throat of the inlet. High and low "flow conveyance index" values would correspond, respectively, to periods of relatively high and low inlet flushing conditions. A consistent pattern obtained from this analysis, wherein high and low index values corresponded with high and low shoreline movements. Additionally, the plot of rates of shore movements against rates of change of "flow conveyance index" was fitted with a simple linear regression line having a positive correlation coefficient of 0.85. Further analyses of the mean distribution of the shoals within the throat of the inlet demonstrated the cause of time-varying rates of movement of points along the spiriferous east shoreline of the inlet. Shoreline movement rates were plotted on a time-space plane and isolines of shore movement rates contoured. The result was a three-dimensional image of shore movement rates over time and distance. The position of the centroid of the inlet shoal distribution at different times was superimposed upon the three-dimensional image. This revealed that variations of shoreline movement rates along the shore at any point in time are dependent on the mean position of the inlet shoal distribution. Also, the direction of movement of the mean position of the inlet shoal distribution appeared to indicate the predominant direction of flushing action, that is, flood or ebb tides.

## 1 INTRODUCTION

Barden Inlet is located along the central portion of the North Carolina coastline and constitutes the physiographic juncture of Shackleford Banks and the south end of Core Banks, see figure 1. This inlet is characterized by an expansive shoal protruding into the inlet's throat from Shackleford Banks, and a resulting curvilinear main flow-conveyance channel juxtaposed with the east or Core Banks shore of the inlet. The effect of flow concentration on the east bank of the inlet has been to mold that shore into a spiraliform indenture. The continuous migration of the primary inlet channel (natural gorge) and concomitant erosion of the Core Banks shore is now threatening eventual damage and possible destruction of the historic Cape Lookout Lighthouse and related peripheral structures located near the inlet. On recognizing the hazard posed by the easterly migration of Barden Inlet, a study was undertaken

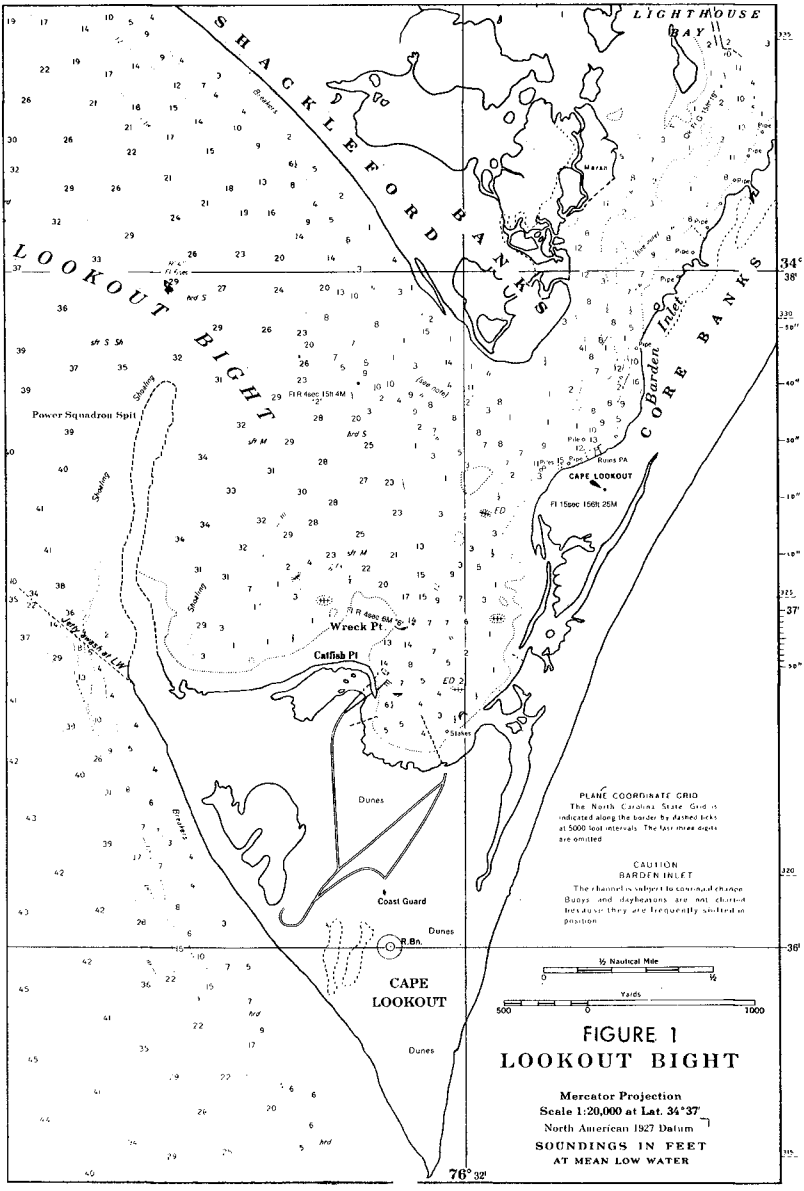



FIGURE 1
LOOKOUT BIGHT

Mercator Projection
Scale 1:20,000 at Lat. 34°37'
North American 1927 Datum
SOUNDINGS IN FEET
AT MEAN LOW WATER

by the U.S. Army Corps of Engineers to determine the causative factors contributing to the problem and to develop appropriate corrective measures. This paper focuses on the evaluation of cause and effect relationships of the problem. It is remarked that prior to initiation of the study reported here, it was suggested by some parties having interest in the problem that the primary cause was the effects of dredging operations conducted in the maintenance of navigation channels approaching the throat of the inlet through its ebb and flood-tide deltas. Accordingly, the first steps in the problem evaluation involved a comparison of the pattern of movements of the shorelines adjacent to the inlet with the record of maintenance dredging in the channels approaching the inlet from its seaward and bay sides. This comparative analysis failed to demonstrate any relationship between dredging and shore movements or inlet migration. Therefore, the next phase of the evaluation examined those factors generally acknowledged to control inlet behavior on sandy shores, viz, sediment influx and tidal discharge. In this case, a very good correlation developed between the intensity and direction of shoreline movements, and an index value representing the relative magnitudes of sediment influx and tidal discharge. Further analyses of the distribution of shoal accumulations within the throat of the inlet demonstrated the cause of time-varying rates of movement of points along the eroding shore on the east side of the inlet.

## 2 EFFECTS - SHORELINE MOVEMENT HISTORY

The pattern of shoreline movements over time was established through the use of aerial photographs of the study area. The available record consisted of 21 photographic coverages during a 37.5-year period extending from Octoher 1940 to April 1978, thus allowing for the evaluation of 20 discrete time spans. Standard methods of evaluating the shoreline movements were employed, that is, a measurement baseline or reference was selected and superimposed on each of the aerial photographs. The baseline was divided into stations at which measurements to the shorelines were made on the respective photographs and compared to determine shoreline movements and rates of movements during the time periods between successive photographs. The baseline passed through the center of the base of the Cape Lookout Lighthouse on a hearing of N 31° E which approximates the orientation of the longitudinal axis of the throat of Barden Inlet. A total of 35 baseline stations, numbered consecutively 1 through 35, were established at a spacing of 30.5 meters (100 feet), with station number 6 being located at the lighthouse. Distances to the shoreline(s) were measured at these stations along transects perpendicular to the baseline and extending toward the inlet. In the evaluation, stations 1 through 35 were utilized to obtain shoreline movement measurements pertaining to the overall Core Banks shoreline of the inlet, and measurements made at stations 4 through 8 were selected to represent conditions of the shoreline in the immediate vicinity of the Cape Lookout Lighthouse building complex, and the transects and related measurements at stations 20 through 27 were extended across the inlet to develop the general pattern of shoreline movement along the inlet's Shackleford Banks shoreline.

In terms of the single longest time span, that is October 1940-April 1978, the results of the photographic analysis were that: (a) the average movement of the entire east shore or Core Banks side of Barden Inlet had been eastward for a distance of 361 meters, giving an average rate of movement of 9.6 m/yr or 0.8 m/mo; (b) the segment of the inlet's east shore in the immediate vicinity of the Cape Lookout Lighthouse had moved easterly for a distance of 388 meters, resulting in an average movement rate of 10.3 m/yr or 0.9 m/mo and by April 1978, this segment of shoreline was within 49 meters of the lighthouse keeper's dwelling and 105 meters from the base of the lighthouse; and (c) the inlet's west shore or Shackleford Banks side had moved westward over a distance of 38 meters, giving an average rate of movement of 1 m/yr or approximately 0.1 m/mo. In regard to short time spans, the rates of shoreline movement deviated substantially from the long-term averages enumerated above. For example, the average movement rate of the east shore varied from as high as 4.4 m/mo in an easterly direction, to as much as 2.8 m/mo in a westerly direction. Additionally, in any given time span, there was great variability in the rates of shoreline movement experienced along the various station transects used in the analysis. In this connection, graphs of the cumulative movements of transect stations were plotted and superimposed, see figure 2. This superposition demonstrated that variations in shore movement rates, transect to transect, were generally occurring in the form of a gradual transition. This occurred because of the remarkably smooth planform curvature of the indentured east bank of Barden Inlet. Indeed, the major portion of this eroding shoreline at the various times that it was photographed could be precisely duplicated by the equation of a logarithmic or equiangular spiral, as illustrated by figure 3.

## 3 CAUSAL FACTORS

In search of a rational causal factor(s) resulting in the inlet channel migration and attendant erosion of the inlet's east bank, the first consideration was given to dredging activities associated with maintaining the seaward and bayward channels approaching the inlet gap. It is remarked that the primary inlet channel (gorge) flowing against the eroding east bank is naturally wide and deep and does not require dredging. With respect to dredging related to the inlet's approach channels through the ebb and flood-tide deltas, the existence, or lack thereof, of two primary trends was sought in terms of the comparison of dredging quantities and shoreline movements, namely: (a) high or low shoreline movement rates corresponding directly with high or low dredging quantities; and (b) high or low shoreline movement rates immediately following high or low dredging quantities. The first comparison to be made was the superposition of histograms of the shoreline movement rates and dredging quantities over time. This comparison failed to indicate any relationship between shoreline behavior and dredging. This was followed with simple linear regression analyses of shoreline movement rates and dredging quantities, considering both the overall indentured east bank of the inlet having a length of 1,036 meters, and a segment of that same shore having a length of 150 meters situated in the immediate vicinity of the Cape Lookout Lighthouse. With shoreline movement rates

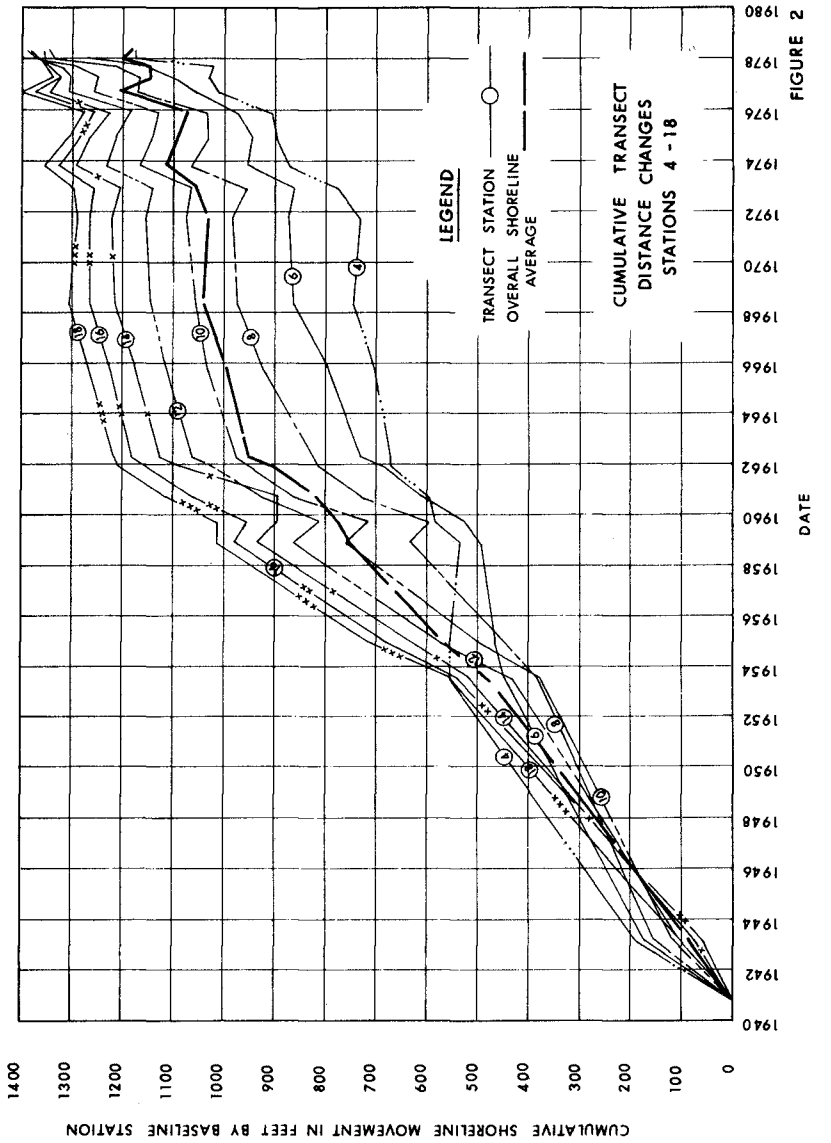
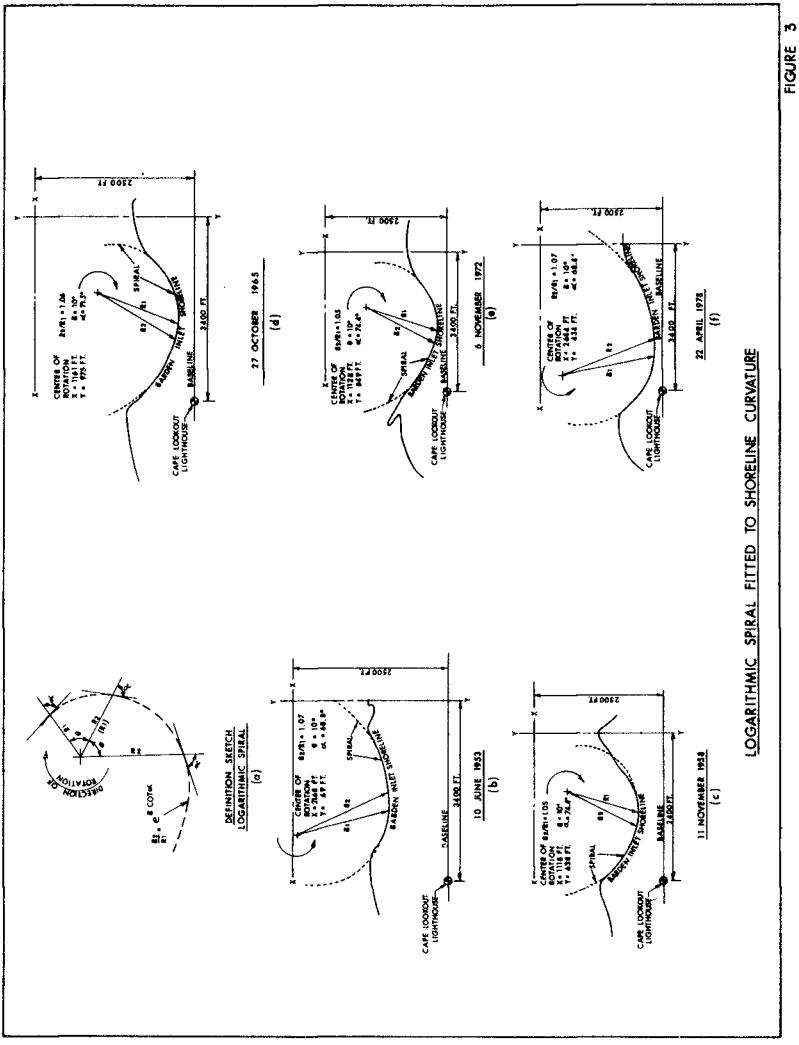

CUMULATIVE TRANSECT
DISTANCE CHANGES
STATIONS 4 - 18
LEGEND
TRANSECT STATION
OVERALL SHORELINE AVERAGE
CUMULATIVE SHORELINE MOVEMENT IN FEET BY BASELINE STATION
DATE
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
1980
1978
1976
1974
1972
1970
1968
1966
1964
1962
1960
1958
1956
1954
1952
1950
1948
1946
1944
1942
1940

FIGURE 2




LOGARITHMIC SPIRAL FITTED TO SHORELINE CURVATURE

FIGURE 3

and dredging quantities as the dependent and independent variables, respectively, the lines of regression fitted through the data points had correlation co-efficients of -0.03 for the overall east bank of the inlet and -0.24 for the small segment of east shore near the lighthouse, see figure 4. This demonstrated numerically that which was evident on inspection of the scatter diagrams, to wit, there was no apparent association between dredging operations in the approach channels and movement of the east bank of the inlet. This was not a particularly startling revelation inasmuch as many inlets on the coast of North Carolina at which there are no navigation channels through the ebb and flood deltas have experienced higher rates of primary inlet channel migration and attendant erosion of the downcoast inlet shoulders than has been experienced at Barden Inlet.

The next step in the evaluation was to examine the available data in terms of the factors generally acknowledged to control inlet behavior on sandy shores. That is, the tidal discharge which acts to flush the inlet and, on the other hand, the intrusive littoral materials depositing in the inlet environment. In the case of Barden Inlet, there was not sufficient data for a quantification of the relative magnitudes of the two opposing factors over the various time periods in which shoreline movements were determined. Accordingly, an implicit approach was taken in analyzing the relative magnitudes of the flushing and siltation factors as reflected in the shoaled and deeper water portions of the throat of Barden Inlet depicted by the available aerial photography. The aerial photographs selected for analysis were those dated 15 July 1960, 3 May 1962, 27 October 1965, 12 April 1968, 15 August 1971, 6 November 1972, 5 October 1973, 15 November 1974, 15 August 1976, 10 August 1977, and 22 April 1978. These particular photographs were selected due to their generally high resolution of submerged features. Moreover, the time spans between photographs were approximately in the range of 1 to 3 years, which should be sufficient time for the inlet to adjust to changed conditions but not so long as to miss important changes.

The analysis of inlet characteristics depicted on the selected photographs was performed on the basis of the geometric framework defined on figure 5, where the X-X and Y-Y axes are identical to those previously described. The longitudinal extent of the inlet was defined as the water area confined between the Y-Y axis and a line extending from and perpendicular to the X-X axis to the Core Banks shoreline through the point of maximum seaward protrusion of the platform shoal which projects into the throat of Barden Inlet from the Shackleford Banks side. The size and distribution of the overall inlet on a given photograph within this framework was characterized by its areal size, the X and Y distances to its centroid, and the first moments of the area taken about the X-X and Y-Y axes. Similarly, the size and distribution of the shoal areas within the inlet framework were defined by their combined areal size, centroidal distances, and first moments about the X-X and Y-Y axes. A measure of the flow conveyance of the inlet was established as the ratio of the first moment of the overall inlet area about the X-X axis to the first moment of the shoal areas about the X-X axis ($M_{X-X}$ (inlet) $M_{X-X}$ (shoal)). This ratio is referred to here as the "flow

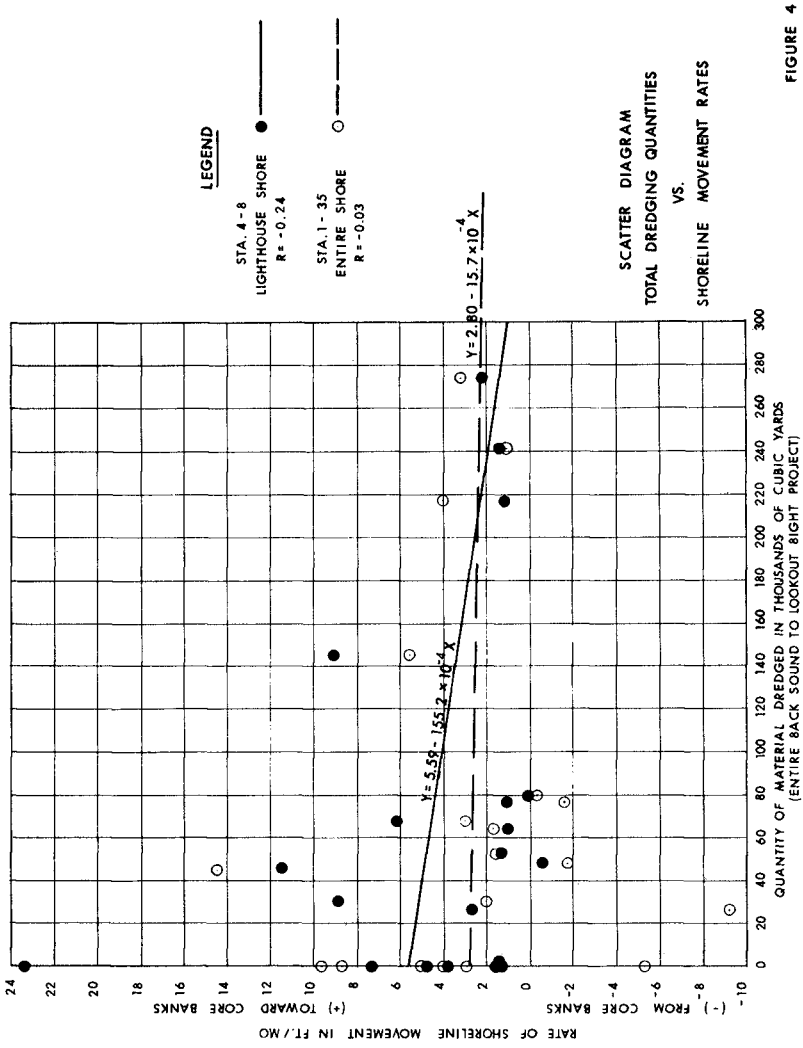

LEGEND
STA. 4 - 8
LIGHTHOUSE SHORE
R = -0.24
STA. 1 - 35
ENTIRE SHORE
R = -0.03
SCATTER DIAGRAM
TOTAL DREDGING QUANTITIES
VS.
SHORELINE MOVEMENT RATES
Y = 2.80 - 15.7 ×10⁻⁴ X
Y = 5.59 - 155.2 ×10⁻⁴ X
RATE OF SHORELINE MOVEMENT IN FT./MO
(+) TOWARD CORE BANKS
(-) FROM CORE BANKS
QUANTITY OF MATERIAL DREDGED IN THOUSANDS OF CUBIC YARDS
(ENTIRE BACK SOUND TO LOOKOUT BIGHT PROJECT)

FIGURE 4

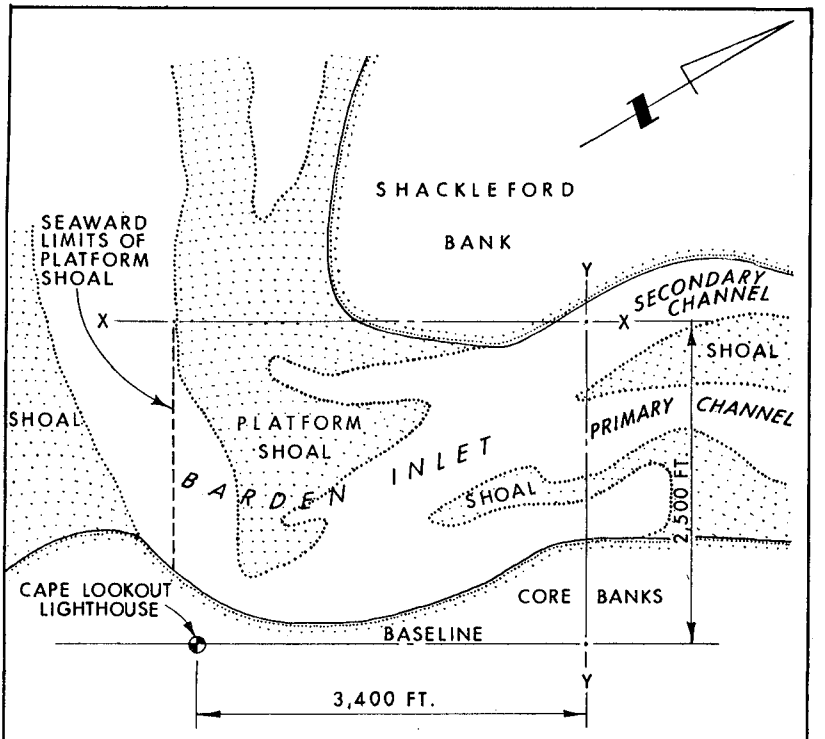



FIGURE 5
DEFINITION SKETCH
FOR
INLET CHARACTERISTICS ANALYSIS

conveyance index." In other words, if the mean distribution of the overall inlet is large by comparison to the mean distribution of the shoal areas therein, it can be expected that the inlet's flow conveyance and flushing capability is high compared to a case where the flow conveyance index is relatively low. The values of inlet and shoal areas, centroidal coordinate distances, first moments about the X-X and Y-Y axes, flow conveyance indices, rates of change of flow conveyance indices, and the weighted average rates of shoreline movements between sequential photographs are listed in table 1. The reader will note the distinctly consistent pattern in which the rates of shoreline movement increase and decrease in accordance with increasing or decreasing flow conveyance indices. This trend is graphically displayed on figure 6 which is a scatter diagram and associated simple linear regression line for shoreline movement rates plotted against the rates of change of the conveyance indices. The linear correlation coefficient (R) has a value of 0.85. In view of the trends described above, it is concluded that the general shoreline behavior on the Core Banks side of Barden Inlet is basically dictated by changes in the tidal flow exchange through the inlet as controlled by increasing and decreasing littoral influx associated with changes in wave energy reaching Shackleford Banks, and increasing and decreasing flushing action which is primarily controlled by wind energy and attendant wind tides and wind drift (movement of water due to wind stress) over the estuarial waters comprised of Pamlico-Core Sounds and Bogue-Back Sounds.

Another important output of the inlet characteristics analysis was the evaluation of the changes in rates of movement of the spiriferous shoreline indenture on the Core Banks side of Barden Inlet generally confined between transect stations 4 and 32. Data plotted on figure 7 graphically display the influence of the longitudinal position of the inlet shoal distribution on the magnitudes of shoreline movement rates at specific points along the indentured shoreline. It will be noted that figure 7 provides a three-dimensional image consisting of a time-space plane on which isolines of shoreline movement rates are plotted. The isolines were contoured from shoreline movement rates of alternate transect station values plotted at the midpoints of the time periods for which the values were computed. Superimposed on the three-dimensional image are the positions (dots) of the centroids of the inlet shoal distributions with respect to the Y-Y axis as referenced to the transect station numbers. The influence of the longitudinal positions of the shoal distribution centroid on the magnitude of shoreline movement rates along the spiriferous shore indenture is clearly evident. During the 1960-1962 period, the shoal centroid position moved bayward with high shore movements being concentrated on the bayward end of the shore (transect stations 22 through 32). This was followed by a gradual seaward movement of the shoal distribution centroid over the period 1962-1972 during which the Core Banks shore retreated at a moderate rate, was stable, or in a state of accretion. This, in turn, was followed by a rapid seaward movement of the centroid in the 1972-1973 period, with concomitant high shore retreat rates concentrated along the seaward end of the shore near the lighthouse. Then, the centroid moved bayward with an accompanying stable or accreting state of the shoreline over the

TABLE 1

Geometric Properties of Inlet Planform Features
Flow Conveyance Indices and Shore Movement Rates

| Date | Area | | Centroidal Coordinates | | | | 1st Area-Moment | | | | Flow Conveyance Index | Rate of Change of Flow Conveyance Index [1] | Weighted Average Rate of Shoreline Movement [2] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $\bar{X}$ | | $\bar{Y}$ | | $M_{y-y}$ $\bar{X}\cdot$Area | | $M_{x-x}$ $\bar{Y}\cdot$Area | | | | |
| | Overall Inlet ($10^6$ ft$^2$) | Inlet Shoals ($10^6$ ft$^2$) | Overall Inlet (ft) | Inlet Shoals (ft) | Overall Inlet (ft) | Inlet Shoals (ft) | Overall Inlet ($10^8$ ft$^3$) | Inlet Shoals ($10^8$ ft$^3$) | Overall Inlet ($10^8$ ft$^3$) | Inlet Shoals ($10^8$ ft$^3$) | $M_{x-x}$ Inlet + $M_{x-x}$ Shores | ($10^{-2}$ mo$^{-1}$) | (ft/mo) |
| 15 Jul 60 | 4.47 | 2.38 | 1,300 | 1,384 | 939 | 655 | 58.13 | 32.92 | 41.99 | 15.58 | 2.70 | | |
| | | | | | | | | | | | | +4.82 | 5.9 |
| 3 May 62 | 4.82 | 2.07 | 1,260 | 1,230 | 999 | 634 | 60.78 | 25.49 | 48.19 | 13.14 | 3.76 | | |
| | | | | | | | | | | | | -2.39 | 1.1 |
| 27 Oct 65 | 5.70 | 2.72 | 1,463 | 1,446 | 995 | 754 | 83.24 | 39.39 | 56.61 | 20.54 | 2.76 | | |
| | | | | | | | | | | | | -0.30 | 1.6 |
| 12 Apr 68 | 6.12 | 3.03 | 1,551 | 1,574 | 1,030 | 777 | 94.92 | 47.77 | 63.04 | 23.58 | 2.67 | | |
| | | | | | | | | | | | | -0.67 | -0.3 |
| 15 Aug 71 | 6.09 | 3.36 | 1,530 | 1,679 | 1,021 | 771 | 93.14 | 56.40 | 62.15 | 25.90 | 2.40 | | |
| | | | | | | | | | | | | +1.08 | 1.7 |
| 6 Nov 72 | 6.07 | 3.06 | 1,491 | 1,641 | 1,035 | 802 | 90.54 | 50.15 | 62.85 | 24.51 | 2.56 | | |
| | | | | | | | | | | | | +9.07 | 5.6 |
| 5 Oct 73 | 6.36 | 2.78 | 1,545 | 1,745 | 1,049 | 677 | 98.3 | 48.52 | 66.76 | 18.82 | 3.55 | | |
| | | | | | | | | | | | | -5.78 | 1.8 |
| 15 Nov 74 | 6.08 | 3.15 | 1,489 | 1,572 | 1,042 | 723 | 90.56 | 49.48 | 63.37 | 22.76 | 2.78 | | |
| | | | | | | | | | | | | +9.33 | 5.3 |
| 15 Aug 76 | 6.75 | 2.68 | 1,612 | 1,991 | 1,098 | 584 | 108.75 | 53.35 | 74.07 | 15.64 | 4.74 | | |
| | | | | | | | | | | | | -8.42 | -4.7 |
| 10 Aug 77 | 6.70 | 2.76 | 1,630 | 1,835 | 1,085 | 707 | 111.91 | 50.67 | 73.0 | 19.52 | 3.73 | | |
| | | | | | | | | | | | | +1.07 | 4.5 |
| 22 Apr 78 | 6.89 | 2.64 | 1,653 | 1,866 | 1,084 | 724 | 113.92 | 52.01 | 74.71 | 19.58 | 3.82 | | |

[1] Positive and negative rates refer to increasing and decreasing rates of change, respectively.
[2] Rates of movement for entire Core Banks shoreline averaged over transect station 1 thru 35.

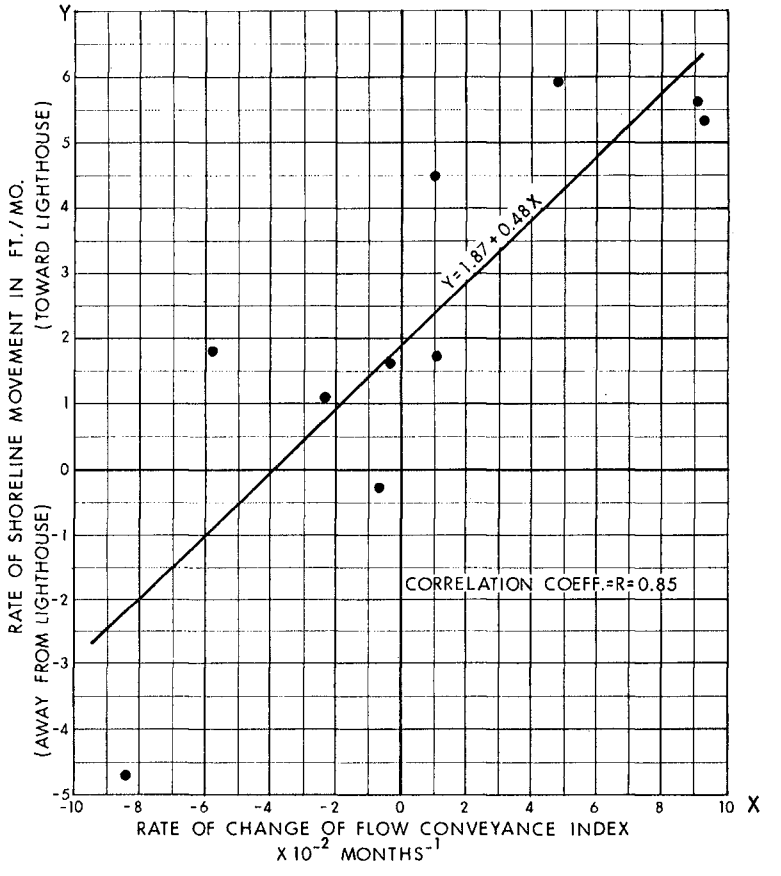



FIGURE 6
SCATTER DIAGRAM

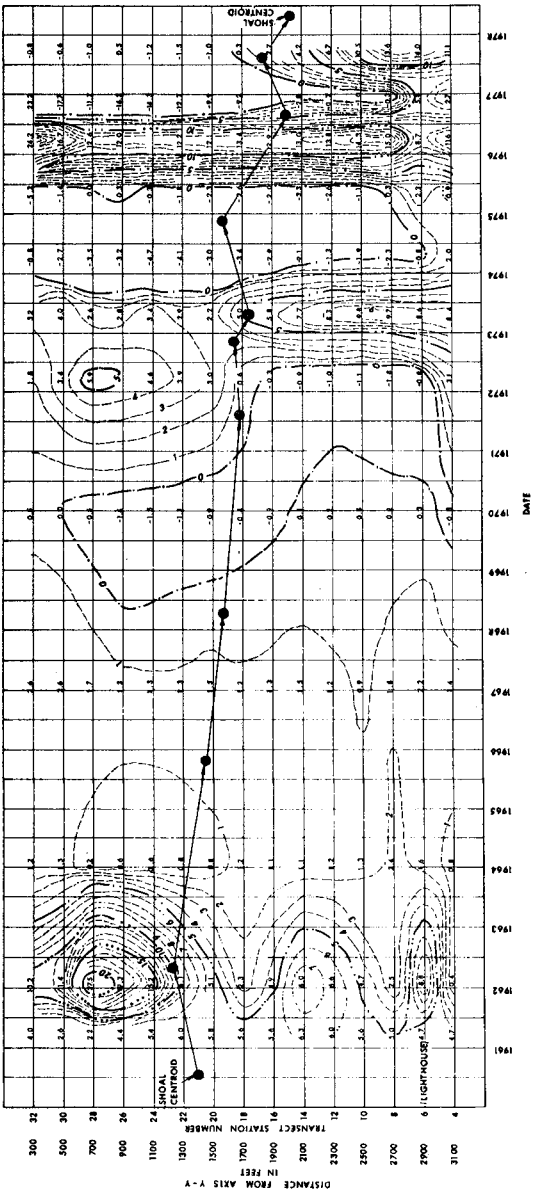
SHORELINE MOVEMENT RATE
-vs-
RATE OF CHANGE
OF
FLOW CONVEYANCE INDEX

1973-1974 time period. Again, in the period 1974-1976, the centroid moved seaward at a rapid rate with generally high erosion rates along the entire shoreline, followed hy a bayward centroid movement in the 1976-1977 period with shore accretion developing. From 1977 to 1978, the centroid moved seaward with high rates of movement occurring along the lighthouse area at the seaward end of the shoreline. Thus, we see that the rates of shoreline movement along different points of the Core Banks side of the inlet are basically controlled by the position of the shoal distribution relative to the shoreline. This, of course, comes from the fact that the shoal distrihution also relates to the major channel positions and orientations and, therefore, the points at which flows are concentrated.

The fundamental cause of the movement of the inlet shoal distribution can be attributed to the direction of the primary inlet flushing action. Major flushing occurs when strong perennial winds from the general northeasterly direction act over the expansive, shallow waters of Pamlico-Core Sounds. This wind action superelevates and forces water movement toward and through Barden Inlet, while concurrently suppressing onshore wave action and littoral materials transport along Shackleford Banks. Thus, the tidal ebb flows are highly efficient in flushing Barden Inlet when winds come from a general northeasterly direction. The results of this phenomenon are reflected in the general trend of seaward movement of the shoal-distribution centroid over the period 1962 to the present; see figure 7. The bayward movement of the shoal-distribution centroid from July 1960 to May 1962 as shown in figure 7 was, in all probability, caused by the high bayward flushing action generated by Hurricane Donna. This storm passed over the inlet on 12 September 1960 and was the last hurricane, to date, causing a significant ocean storm tide along the Shackleford Banks coastal zone. Indeed, it was not only the last significant ocean surge event, but was also the highest storm surge of record for that area. The Donna ocean storm tide reached an elevation of 3.3 meters above mean sea level. At the time of the recorded peak ocean tide, the bay water level was measured at 1.4 meters above mean sea level. Thus, a maximum water level differential of 1.9 meters existed between ocean and bay waters. The flood current velocity through Barden Inlet, as generated by this condition, was computed at 2.4 meters per second. Such a high flow would unquestionably flush the inlet shoal accumulations in a bayward direction. Moreover, as Hurricane Donna moved northward, its radius of maximum winds traversed a line coincident with the long axis of Pamlico Sound, thus tilting the water up at the north end of Pamlico Sound and depressing the water levels in Core Sound and the south end of Pamlico Sound. This resulted in an unusually long period of bayward flushing at Barden Inlet.

## 4 CONCLUSIONS

The investigation of Barden Inlet in reference to migration of the primary inlet channel (gorge) and the attendant erosion of the east bank demonstrates that one cannot, a priori, relate dredging operations through the ebb and flood-tide deltas of small coastal inlets with inlet migration in general nor with the rates of migration. The availability




ISOLINES OF RATE OF SHORELINE MOVEMENT IN FEET PER MONTH WITH RESPECT TO TIME AND SHORELINE STATIONING

FIGURE 7

of aerial photographs of Barden Inlet allowed for an implicit analysis of the causal factors associated with inlet processes at that site, resulting in findings consonant with the accepted concepts of factors influencing inlet behavior, namely, tidal discharge and the influx of littoral material.